

Mode-locked oscillators in the positive and negative dispersion regimes: scenarios of destabilization

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ABSTRACT

We analyze the influence of spectrally modulated dispersion and loss on the stability of mode-locked oscillators. In the negative dispersion regime, a soliton oscillator can be stabilized in a close proximity to zero-dispersion wavelength, when spectral modulation of dispersion and loss are strong and weak, respectively. If the dispersion is close to zero but positive, we observe *chaotic* mode-locking or a stable coexistence of the pulse with the CW signal. The results are confirmed by experiments with a Cr:YAG oscillator.

Keywords: Femtosecond laser pulses, Mode-locked oscillator, Solid-state laser

1. INTRODUCTION

Oscillators providing stable sub-100 fs pulses in the near-infrared region around 1.5 μm are of interest for a number of applications including infrared continuum generation^{1,2} and high-sensitivity gas spectroscopy.³ To date, the typical realization of such sources is based on a femtosecond Er: fiber oscillator with an external pulse amplification. A promising alternative to such combination is a solid-state Cr⁴⁺:YAG mode-locked oscillator.^{4,5} Such an oscillator allows a direct diode pumping and possesses the gain band providing the few-optical cycle pulses.

However, attempts to increase the pulse energy in a Cr:YAG oscillator is limited by its relatively small gain coefficient. Because of the low gain, the oscillator has to operate with low output couplers and, thereby, the intra-resonator pulse energy has to be high. As a result, the instabilities appear.^{4,6} To suppress the instabilities in the negative dispersion regime (NDR) a fair amount of the group-delay-dispersion (GDD) is required. The resulting pulse is a relatively long soliton with reduced peak power. Such a pulse is nearly transform-limited and is not compressible. A remedy is to use the positive dispersion regime (PDR), when the pulse is stabilized due to substantial stretching (up to few picoseconds) caused by a large chirp.⁷ Such a pulse is dispersion-compressible down to few tens of femtoseconds.

For both NDR and PDR, the oscillator will eventually become unstable at high power. The main scenarios of the pulse destabilization have been identified with the multipulsing in the NDR⁶ and the CW-amplification in the PDR.⁸ It has been found, that the higher-order dispersions (i.e., the frequency dependent GDD) and losses significantly modify the stability conditions.^{9,10} Hence, the study of the stability conditions affected by both linear and nonlinear processes inherent in a mode-locked oscillator remains an important task.

Here, we present a study of the destabilization mechanisms of a Cr:YAG mode-locked oscillator, operating in both NDR and PDR. We put a special emphasis on the influence of the spectral dependence of GDD and losses on the oscillator stability.

2. DESTABILIZATION OF A MODE-LOCKED OSCILLATOR IN THE PDR

The Cr:YAG oscillator has been built on the basis of the scheme published in Refs.^{2,11} The mode-locking and the dispersion control were provided by SESAM and chirped-mirrors (CMs), respectively. The GDD of intra-resonator elements as well as the net-GDD are shown in Fig. 1. As a result of the GDD variation of the 51-layer CMs and the uncertainty of the SESAM dispersion, the real net-GDD has some uncertainty, too (gray region in Fig. 1, a).

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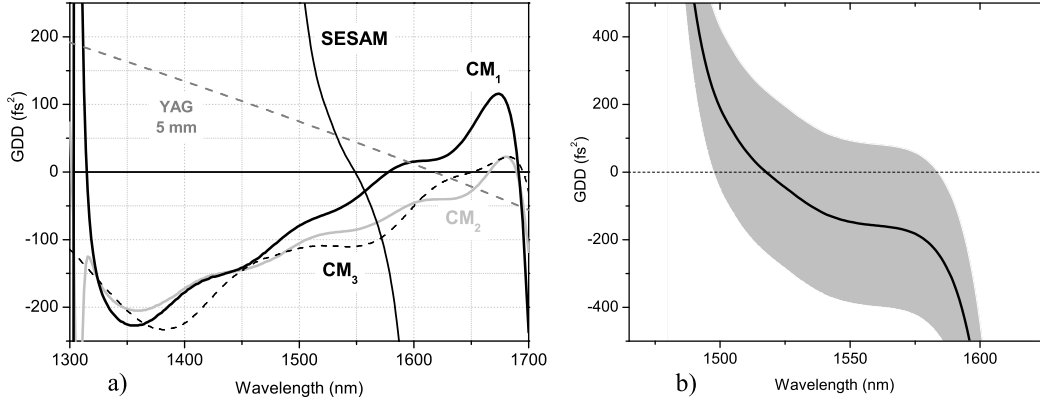


Figure 1. a) GDD of three sets of chirped mirrors CM (as designed), the YAG crystal, and the SESAM. b) The net dispersion of the resonator of Cr⁴⁺:YAG oscillator. Black line: as designed, grey area - uncertainty region due to the chirped mirrors.

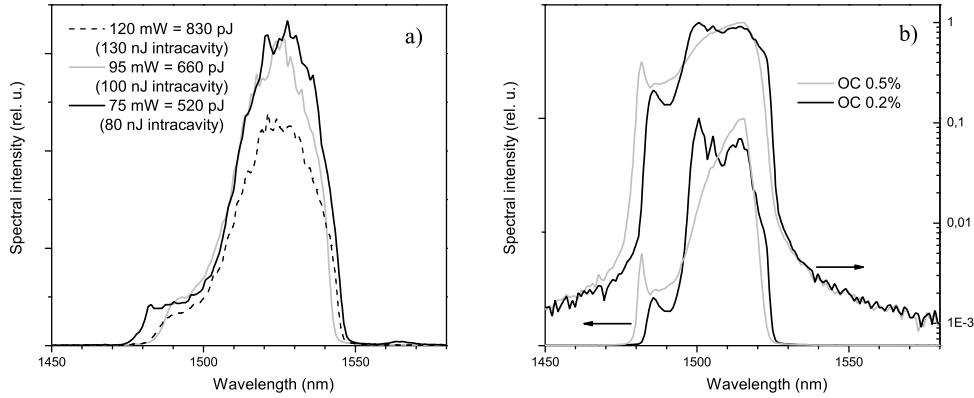


Figure 2. a) Spectra of the Cr:YAG oscillator operating in the PDR at different values of intracavity pulse energy. b) Spectra of the Cr:YAG oscillator with different output couplers.

Selection of the different CM combinations allows over- and under-compensation of the dispersion. Selecting a 2CM₁+2CM₁ allows stabilizing the oscillator at the 144.5 MHz pulse repetition rate and 150 mW average output power. The corresponding spectra shown in Fig. 2 have truncated profiles, that is typical for an oscillator operating in the PDR.⁸

To study the stability limits of PDR, the numerical simulations based on the nonlinear cubic-quintic complex Ginzburg-Landau model¹² have been realized. The evolution of the slowly varying field envelope $A(z, t)$ can be described in the following way:

$$\frac{\partial A}{\partial z} = \sigma(\omega_0) A + \alpha(\omega_0) \tau^2 \frac{\partial^2 A}{\partial t^2} - \rho(\omega - \omega'_0) A + i\beta(\omega - \omega_0) A + \{[\kappa - i\gamma] P - \kappa\zeta P^2\} A. \quad (1)$$

Here z is the propagation distance normalized to the cavity length L_{cav} (i.e., the cavity round-trip number), t is

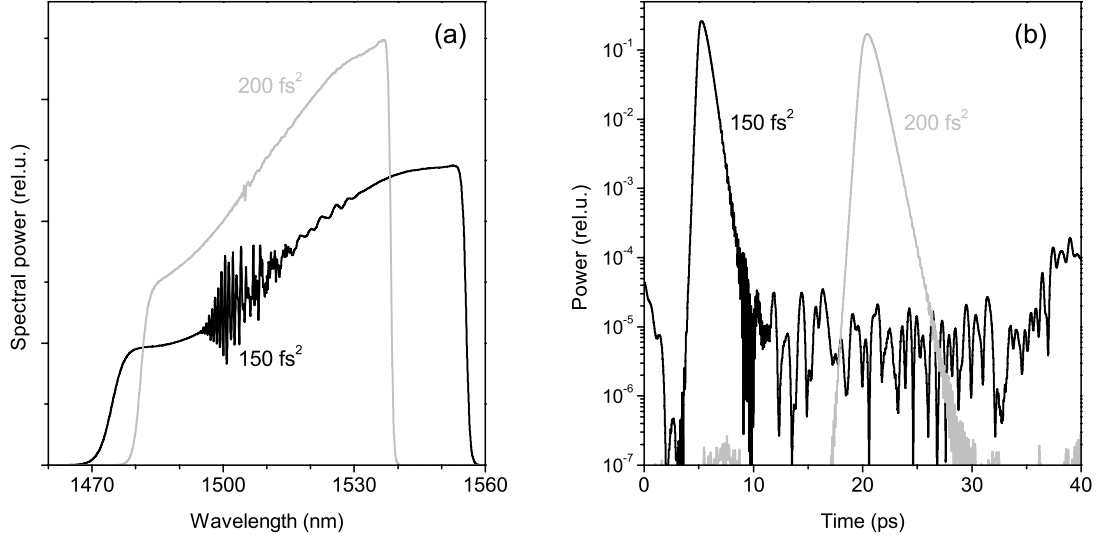


Figure 3. (a) - Simulated spectra, (b) - intensity profiles in the positive dispersion regime. GDD corresponds to $\beta_2 = 200$ fs^2 (gray curves) and 150 fs^2 (black curves).

the local time. The reference time frame moves with the pulse group-velocity defined at the reference frequency ω_0 corresponding to the gain maximum at $\lambda_0 \approx 1.5 \mu\text{m}$. The term $\alpha(\omega_0)\tau^2\partial^2 A/\partial t^2$ describes the action of the gain spectral profile in parabolic approximation. Parameter $\alpha(\omega_0) = 0.028$ is the saturated gain coefficient at ω_0 , and it is close to the net-loss value at this frequency. Parameter $\tau = 9.5 \text{ fs}$ is the inverse gain bandwidth. The term $\beta(\omega - \omega_0)A$ describes the net-GDD action in the Fourier domain. The term $\rho(\omega - \omega'_0)A$ describes the action of the net loss spectral profile in the Fourier domain. Frequency ω'_0 corresponds to the transmission minimum of the output coupler at $\lambda'_0 \approx 1.53 \mu\text{m}$. Parameter $\gamma = 1.8 \text{ MW}^{-1}$ describes the self-phase modulation inside the active medium, $\kappa = 0.05\gamma$ is the self-amplitude modulation parameter, $\zeta = 0.6\gamma$ is the parameter defining saturation of the self-amplitude modulation with power.⁸

Parameter $\sigma(\omega_0)$ is the difference between the saturated gain $\alpha(\omega_0)$ and the net loss at the reference frequency ω_0 . It was assumed, that this parameter depends on the full pulse energy: $\sigma(E) \approx \frac{d\sigma}{dE}|_{E=E^*} (E - E^*) = \delta(E/E^* - 1)$, where E^* corresponds to the full energy stored inside an oscillator in the CW regime.⁸ Parameter $\delta \equiv \frac{d\sigma}{dE}|_{E=E^*}$ equals to -0.03.

It was found, that the GDD decrease in the PDR results in the CW-amplification (see the black curve in Fig. 3). The CW-amplification appears in the vicinity of the spectral net-loss minimum, where the saturated net-gain becomes positive. The latter occurs because gain saturation decreases with GDD approaching to zero. Simultaneously, the spectrum gets broader, which enhances the spectral losses and, thereby reduces the pulse energy.

When the GDD is spectrally dependent (i.e., there are the higher-order dispersions), the scenario of destabilization with an approaching of GDD to zero changes (Fig. 4, a). In this case, the chaotic oscillations of the peak power appear (*chaotic mode-locking*⁹). The spectrum edges in such a regime become smoothed and the spectrum shifts to the local GDD-minimum. It was found,⁹ that the PDR stability is improved in the vicinity of the local minimum of the GDD (i.e., when the fourth-order dispersion is positive). Fig. 4, b shows the spectrum (gray curve) corresponding to the lower on GDD stability border of PDR. The spectrum is asymmetrical, “M-shape”, and the spectrum maximum is situated in the vicinity of the GDD local minimum.

3. DESTABILIZATION OF A MODE-LOCKED OSCILLATOR IN THE NDR

In the NDR and in the absence of higher-order dispersions, the pulse can be stabilized only by a significant amount of the negative GDD ($\approx -9900 \text{ fs}^2$ in our case). However, the contribution of higher-order dispersions can

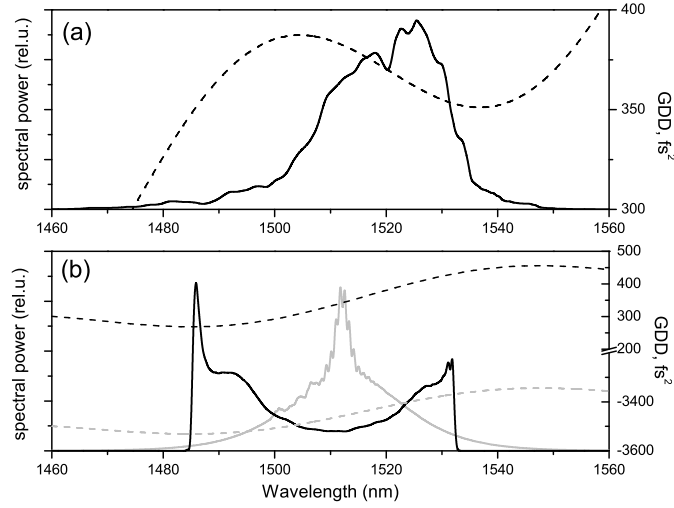


Figure 4. Simulated spectra (solid curves), with different net-GDD (dashed curves). $\lambda_0 = 1.54 \mu\text{m}$, other parameters correspond to Fig. 3, the case without spectrally-dependent losses.

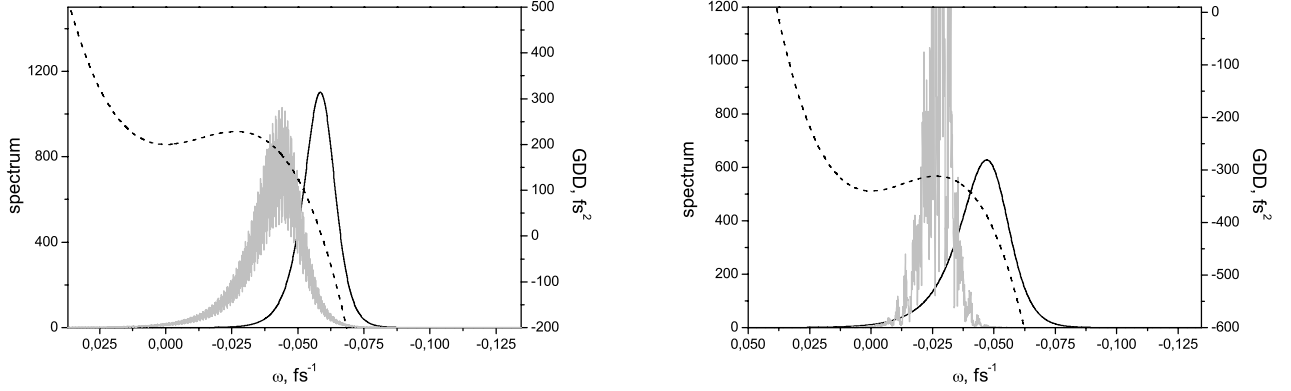


Figure 5. GDD spectral profiles (dashed) and corresponding simulated pulse spectra without (black) and with (gray) spectral dependence of the losses. The losses are assumed to have a local minimum at $1.53 \mu\text{m}$ about -0.025 fs^{-1} .

stabilize the pulse in the immediate vicinity of zero GDD (black curves in Fig. 5). The pulse is stable if even a part of spectrum is situated within the positive GDD range (left picture in Fig. 5).

However, the NDR stability in the vicinity of zero GDD is very sensitive to the spectral dependence of the losses. Presence of such dependence leads to the multipulsing (harmonic mode-locking, gray curves in Fig. 5). As it was found,⁶ the source of multipulsing is the insufficiently saturated net-gain, which appears in the vicinity of zero GDD due to decrease of the pulse energy caused by the spectral losses.

In analogy with the PDR, the spectral dependence of GDD can initiate the chaotic mode-locking, when the negative GDD approaches zero (gray curve in Fig. 4). The spectrum shifts from the region, where the local minimum of GDD is located. This behaviour is reverse in the comparison with that in the PDR. Thus, the stability regions of PDR and NDR are disjointed by a region of chaotic mode-locking in the vicinity of zero GDD.

Just as the “M-shaped” spectra appear in the PDR, when the fourth-order dispersion leads to the GDD growth on the spectrum edges, the humps of the spectrum envelope exist in the NDR (Fig. 6). In contrast to the PDR, the local spectral maxima appear in the vicinity of local maxima of GDD.

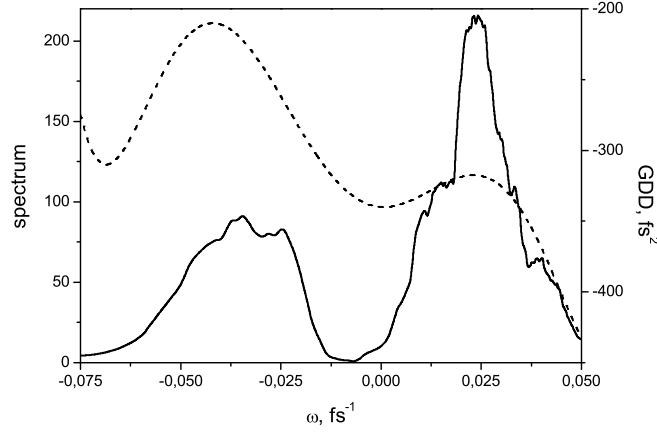


Figure 6. GDD spectral profile (dashed) and corresponding simulated pulse spectrum in the negative dispersion regime with modulated dispersion and no spectral dependence of the losses.

4. CONCLUSIONS

We have studied stability conditions of a Cr:YAG oscillator in both, positive and negative dispersion regimes. In the NDR, the oscillator exhibits strong tendency to harmonic mode-locking (i.e., multipulsing), which can be suppressed only by a significant amount of the negative GDD. The GDD value providing the multipulsing suppression depends on the GDD shape, so that the soliton-like regime can exist even if the part of the spectrum lies within the positive dispersion range. The spectrum maximum shifts in the region, where the local maximum of GDD is located. The presence of the spectrally-dependent losses enhances the multipulsing in the vicinity of zero GDD. When the GDD is frequency-dependent, the positive- and negative-dispersion single-pulse regimes are disjointed by the GDD ranges with chaotic and harmonic mode locking. In the PDR, approaching of the GDD to zero results in a CW-amplification or a chaotic mode-locking. The last regime appears if the GDD is frequency-dependent. The stabilizing factor of such frequency dependence is the presence of a local minimum (for the PDR) or maximum (for the NDR) of GDD in the vicinity of the pulse spectrum.

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REFERENCES

- [1] E. Sorokin, V. L. Kalashnikov, S. Naumov, J. Teipel, F. Warken, H. Giessen and I. T. Sorokina, “Intra- and extra-cavity spectral broadening and continuum generation at 1.5 μm using compact low-energy femtosecond Cr:YAG laser,” *Appl. Phys. B* **77**, pp. 197–204, 2003.
- [2] V. L. Kalashnikov, E. Sorokin, S. Naumov, I. T. Sorokina, V. V. Ravi Kanth Kumar and K. George, “Low-threshold supercontinuum generation from an extruded SF6 PCF using a compact Cr⁴⁺:YAG laser,” *Appl. Phys. B* **79**, pp. 591–596, 2004.
- [3] J. Mandon, G. Guelachvili, N. Picqué, F. Druon and P. Georges, “Femtosecond laser Fourier transform absorption spectroscopy,” *Opt. Lett.* **32**, pp. 1677–1679, 2007.
- [4] S. Naumov, E. Sorokin, V. L. Kalashnikov, G. Tempea, I. T. Sorokina, “Self-starting five optical pulse generation in Cr⁴⁺:YAG laser,” *Appl. Phys. B* **76**, pp. 1–11, 2003.
- [5] C. G. Leburn, A. A. Lagatsky, C. T. A. Brown, and W. Sibbett, “Femtosecond Cr⁴⁺:YAG laser with 4 GHz pulse repetition rate,” *Electron. Lett.* **40**, pp. 805–807, 2004.

- [6] V. L. Kalashnikov, E. Sorokin, and I. T. Sorokina, "Multipulse operation and limits of the Kerr-lens mode-locking stability," *IEEE J. Quant. Electron.* **39**, pp. 323–336, 2003.
- [7] S. Naumov, A. Fernandez, R. Graf, P. Dombi, F. Krausz, and A. Apolonski, "Approaching the microjoule frontier with femtosecond laser oscillators," *New Journal of Physics* **7**, p. 216, 2005.
- [8] V. L. Kalashnikov, E. Podivilov, A. Chernykh, A. Apolonski, "Chirped-pulse oscillators: theory and experiment," *Appl. Phys. B* **83**, pp. 503–510, 2006.
- [9] V. L. Kalashnikov, A. Fernández, A. Apolonski, "High-order dispersion in chirped-pulse oscillators," *Optics Express*, pp. 4206–4216, 2008.
- [10] V. L. Kalashnikov, E. Sorokin, S. Naumov, and I. T. Sorokina, "Spectral properties of the Kerr-lens mode-locked Cr^{4+} :YAG laser," *J. Opt. Soc. Am.* **20**, pp. 2084–2092, 2003.
- [11] S. Naumov, E. Sorokin, I. T. Sorokina, *OSA Trends in Optics and Photonics vol. 83, Advanced Solid-State Photonics* **83**, p. 163, 2003.
- [12] N. N. Akhmediev, A. Ankiewicz, *Solitons: nonlinear pulses and beams*, Chapman & Hall, London, 1997.